REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
06-11-2014	Final Report	15-May-2009 - 15-Aug-2014

4. TITLE AND SUBTITLE

Final Report: A Self-Adaptive Energy-Efficient Framework for Large Unattended Wireless Sensor Networks

5a. CONTRACT NUMBER
W911NF-09-1-0154

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS

Yuanyuan Yang

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Research Foundation of SUNY at Stony Bro
W5510 Melville Library

Stony Brook, NY   11794 -3362

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
53410-NS.62

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The objective of this research is to study energy efficient self-adaptive schemes for wireless sensor networks. During the five years of the project, we have made significant progress along several research directions. We have investigated several research issues in mobile data gathering in wireless sensor networks, which are essentially cross-layer solutions to reduce sensor energy consumption and shortening data gathering latency. We have also studied adaptive compression for delay-sensitive data gathering, as well as the utilization of the lossy nature of wireless links to increase energy efficiency of the network. We have proposed a three-layer framework for mobile

15. SUBJECT TERMS
wireless sensor networks, energy efficiency, adptive, data gathering, mobility, multiple-input-multiple-output (MIMO) technique

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Yuanyuan Yang
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					631-632-8474

Report Title

Final Report: A Self-Adaptive Energy-Efficient Framework for Large Unattended Wireless Sensor Networks

ABSTRACT

The objective of this research is to study energy efficient self-adaptive schemes for wireless sensor networks. During the five years of the project, we have made significant progress along several research directions. We have investigated several research issues in mobile data gathering in wireless sensor networks, which are essentially cross-layer solutions to reduce sensor energy consumption and shortening data gathering latency. We have also studied adaptive compression for delay-sensitive data gathering, as well as the utilization of the lossy nature of wireless links to increase energy efficiency of the network. We have proposed a three-layer framework for mobile data gathering to achieve better scalability. Moreover, to achieve optimal performance for mobile data gathering, we have formulated two optimization problems in a utility maximization framework and designed distributed algorithms to solve these problems. Finally, we have developed an advanced wireless testbed for validating the algorithms designed.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received   Paper

08/28/2012 20.00 Chi Ma, Yuanyuan Yang. A Battery-Aware Scheme for Routing in Wireless Ad Hoc Networks,
                  IEEE Transactions on Vehicular Technology, (10 2011): 3919. doi: 10.1109/TVT.2011.2166093

08/28/2012 30.00 Miao Zhao, Yuanyuan Yang. Optimization-Based DistributedAlgorithms for Mobile Data Gatheringin
                  Wireless Sensor Networks,
                  IEEE Transactions on Mobile Computing, (10 2012): 1464. doi: 10.1109/TMC.2011.178

08/28/2012 29.00 Yuanyuan Yang, Xi Deng. Online Adaptive Compression in Delay Sensitive Wireless Sensor Networks,
                  IEEE Transactions on Computers, (10 2012): 1429. doi: 10.1109/TC.2011.174

08/28/2012 28.00 Xi Deng, Yuanyuan Yang, Sangjin Hong. A Flexible Platform for Hardware-Aware Network Experiments
                  and a Case Study on Wireless Network Coding,
                  IEEE/ACM Transactions on Networking, (03 2012): 0. doi: 10.1109/TNET.2012.2191156

08/28/2012 27.00 Miao Zhao, Yuanyuan Yang. Packet scheduling with joint design of MIMO and network coding,
                  Journal of Parallel and Distributed Computing, (03 2012): 376. doi: 10.1016/j.jpdc.2011.12.001

08/28/2012 25.00 Shan Chu, Xin Wang, Yuanyuan Yang. Exploiting Cooperative Relay for High Performance
                  Communications in MIMO Ad Hoc Networks,
                  IEEE Transactions on Computers, (11 2011): 0. doi: 10.1109/TC.2012.23

08/30/2013 34.00 Dawei Gong, Yuanyuan Yang. On-Line AP Association Algorithms for 802.11n WLANs with
                  Heterogeneous Clients,
                  IEEE Transactions on Computers, (2013): 0. doi: 10.1109/TC.2013.156

08/30/2013 35.00 Yuanyuan Yang, Xi Deng. Communication Synchronization in Cluster-Based Sensor Networks for Cyber-
                  Physical Systems,
                  IEEE Transactions on Emerging Topics in Computing, (2013): 0. doi: 10.1109/TETC.2013.2273219

08/30/2013 36.00 Shan Chu, Xin Wang, Yuanyuan Yang. Adaptive Scheduling in MIMO-based Heterogeneous Ad hoc
                  Networks,
                  IEEE Transactions on Mobile Computing, (2013): 0. doi: 10.1109/TMC.2013.112

08/30/2013 37.00 Yuanyuan Yang, Zhexi Pan, Dawei Gong. Energy-efficient clustering in lossy wireless sensor networks,
                  Journal of Parallel and Distributed Computing, (9 2013): 0. doi: 10.1016/j.jpdc.2013.02.012

08/30/2013 38.00 Yuanyuan Yang, Miao Zhao, Ming Ma. Tour Planning for Mobile Data-Gathering Mechanisms in Wireless
                  Sensor Networks,
                  IEEE Transactions on Vehicular Technology, (05 2013): 0. doi: 10.1109/TVT.2012.2229309

08/31/2011 2.00 Miao Zhao, Ming Ma, Yuanyuan Yang. Applying Opportunistic Medium Access and Multiuser MIMO
                  Techniques in Multi-channel Multi-radio WLANs,
                  Mobile Networks and Applications, (1 2009): 0. doi: 10.1007/s11036-008-0149-y

08/31/2011 1.00 Zhenghao Zhang, Yuanyuan Yang, Miao Zhao. Enhancing Downlink Performance in Wireless Networks
                  by Simultaneous Multiple Packet Transmission,
                  IEEE Transactions on Computers, (05 2009): 0. doi: 10.1109/TC.2008.191

08/31/2011 3.00 Xiaojing Xiang, Xin Wang, Yuanyuan Yang. Stateless Multicasting in Mobile Ad Hoc Networks,
                  IEEE Transactions on Computers, (08 2010): 0. doi: 10.1109/TC.2010.102

08/31/2011 4.00 Miao Zhao, Ming Ma, Yuanyuan Yang. Efficient Data Gathering with Mobile Collectors and Space-Division Multiple Access Technique in Wireless Sensor Networks,
IEEE Transactions on Computers, (03 2011): 0. doi: 10.1109/TC.2010.140

08/31/2011 5.00 Xiaojing Xiang, Xin Wang, Yuanyuan Yang. Supporting Efficient and Scalable Multicasting over Mobile Ad Hoc Networks,
IEEE Transactions on Mobile Computing, (04 2011): 0. doi: 10.1109/TMC.2010.176

08/31/2011 6.00 Miao Zhao, Yuanyuan Yang. Bounded Relay Hop Mobile Data Gathering in Wireless Sensor Networks,
IEEE Transactions on Computers, (01 2010): 0. doi: 10.1109/TC.2010.219

08/31/2011 8.00 Miao Zhao, Yuanyuan Yang. Optimization Based Distributed Algorithms for Mobile Data Gathering in Wireless Sensor Networks,
IEEE Transactions on Mobile Computing, (01 2011): 0. doi: 10.1109/TMC.2011.178

11/06/2014 50.00 Miao Zhao, Yuanyuan Yang, Cong Wang. Mobile Data Gathering with Load Balanced Clustering and Dual Data Uploading in Wireless Sensor Networks,
IEEE Transactions on Mobile Computing, (2014): 0. doi: 10.1109/TMC.2014.2338315

11/06/2014 49.00 Miao Zhao, Yuanyuan Yang, Dawei Gong. A multi-channel cooperative MIMO MAC protocol for clustered wireless sensor networks,
Journal of Parallel and Distributed Computing, (11 2014): 3098. doi: 10.1016/j.jpdc.2014.07.012

11/06/2014 51.00 Songtao Guo, Cong Wang, Yuanyuan Yang. Joint Mobile Data Gathering and Energy Provisioning in Wireless Rechargeable Sensor Networks,
IEEE Transactions on Mobile Computing, (12 2014): 0. doi: 10.1109/TMC.2014.2307332

11/06/2014 52.00 Miao Zhao, Ji Li, Yuanyuan Yang. A Framework of Joint Mobile Energy Replenishment and Data Gathering in Wireless Rechargeable Sensor Networks,
IEEE Transactions on Mobile Computing, (12 2014): 0. doi: 10.1109/TMC.2014.2307335

11/06/2014 53.00 Dawei Gong, Miao Zhao, Yuanyuan Yang. Distributed channel assignment algorithms for 802.11n WLANs with heterogeneous clients,
Journal of Parallel and Distributed Computing, (05 2014): 0. doi: 10.1016/j.jpdc.2014.01.009

11/06/2014 54.00 . NETWRAP: An NDN Based Real-TimeWireless Recharging Framework for Wireless Sensor Networks,
IEEE Transactions on Mobile Computing, (06 2014): 0. doi: 10.1109/TMC.2013.2296515

11/06/2014 55.00 Songtao Guo, Chuangyin Dang, Yuanyuan Yang. Joint Optimal Data Rate and Power Allocation in Lossy Mobile Ad Hoc Networks with Delay-Constrained Traffics,
IEEE Transactions on Computers, (2014): 0. doi: 10.1109/TC.2013.2296043

11/06/2014 56.00 Dawei Gong, Yuanyuan Yang. Low-Latency SINR-Based Data Gathering in Wireless Sensor Networks,
IEEE Transactions on Wireless Communications, (06 2014): 0. doi: 10.1109/TWC.2014.042114.130347

TOTAL: **26**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>   <u>Paper</u>

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>   <u>Paper</u>

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

08/28/2012 21.00   Ji Li, Yuanyuan Yang, Miao Zhao. Joint mobile energy replenishment and data gathering in wireless rechargeable sensor networks,
Proceeding ITC '11 Proceedings of the 23rd International Teletraffic Congress. 06-SEP-11, . : ,

08/28/2012 33.00   Yang Qin, Xiangtai Xu, Yuanyuan Yang, Jiali Zhou, Hongpeng Wang. Joint Generation Network Coding in Unreliable Wireless Networks,
IEEE Globecom 2011 proceedings. 05-DEC-11, . : ,

08/28/2012 32.00   Yuanyuan Yang, Hewu Li, Dawei Gong. High-Throughput Collision-Free Client Polling in Multi-AP WLANs,
IEEE Globecom 2011 proceedings. 05-DEC-11, . : ,

08/28/2012 31.00   Yuanyuan Yang, Songtao Guo. A distributed optimal framework for mobile data gathering with concurrent data uploading in wireless sensor networks,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/28/2012 26.00   Yuanyuan Yang, Dawei Gong. AP association in 802.11n WLANs with heterogeneous clients,
IEEE INFOCOM 2012 - IEEE Conference on Computer Communications. 25-MAR-12, Orlando, FL, USA. : ,

08/28/2012 24.00   Xi Deng, Yuanyuan Yang. An Efficient MAC Multicast Protocol for Reliable Wireless Communications with Network Coding,
2011 IEEE Global Communications Conference (GLOBECOM 2011). 05-DEC-11, Houston, TX, USA. : ,

08/28/2012 23.00   Songtao Guo, Yunqiang Zhang, Yuanyuan Yang. Distributed Power and Rate Allocation with Fairness for Cognitive Radios in Wireless Ad Hoc Networks,
2011 IEEE Global Communications Conference (GLOBECOM 2011). 05-DEC-11, Houston, TX, USA. : ,

08/28/2012 22.00   Dawei Gong, Miao Zhao, Yuanyuan Yang. Topology control and channel assignment in lossy wireless sensor networks,
Teletraffic Congress (ITC), 2011 23rd International. 06-SEP-11, . : ,

08/30/2013 44.00   Cong Wang, Yuanyuan Yang, Ji Li. Stochastic mobile energy replenishment and adaptive sensor activation for perpetual wireless rechargeable sensor networks,
2013 IEEE Wireless Communications and Networking Conference (WCNC). 07-APR-13, Shanghai, Shanghai, China. : ,

08/30/2013 45.00   Dawei Gong, Yuanyuan Yang. Low-latency SINR-based data gathering in wireless sensor networks,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/30/2013 46.00   Songtao Guo, Cong Wang, Yuanyuan Yang. Mobile data gathering with Wireless Energy Replenishment in rechargeable sensor networks,
IEEE INFOCOM 2013 - IEEE Conference on Computer Communications. 14-APR-13, Turin, Italy. : ,

08/30/2013 47.00   Ji Li, Miao Zhao, Yuanyuan Yang. OWER-MDG: A novel energy replenishment and data gathering mechanism in wireless rechargeable sensor networks,
GLOBECOM 2012 - 2012 IEEE Global Communications Conference. 03-DEC-12, Anaheim, CA, USA. : ,

08/30/2013 39.00 Yuanyuan Yang, Xi Deng. Cluster Communication Synchronization in Delay-Sensitive Wireless Sensor Networks,
2013 IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS). 20-MAY-13, Cambridge, MA, USA. : ,

08/30/2013 40.00 Dawei Gong, Yuanyuan Yang. Distributed Algorithms for Joint Routing and Frame Aggregation in 802.11n Wireless Mesh Networks,
2013 IEEE International Symposium on Parallel & Distributed Processing (IPDPS). 20-MAY-13, Cambridge, MA, USA. : ,

08/30/2013 41.00 Cong Wang, Yuanyuan Yang, Ji Li, Fan Ye. Multi-vehicle Coordination for Wireless Energy Replenishment in Sensor Networks,
2013 IEEE International Symposium on Parallel & Distributed Processing (IPDPS). 20-MAY-13, Cambridge, MA, USA. : ,

08/30/2013 42.00 Miao Zhao, Yuanyuan Yang, Dawei Gong. Channel assignment in multi-rate 802.11n WLANs,
2013 IEEE Wireless Communications and Networking Conference (WCNC). 07-APR-13, Shanghai, Shanghai, China. : ,

08/30/2013 43.00 Yuanyuan Yang, Xingfu Zhu, Songtao Guo. Optimal and distributed resource allocation in lossy mobile ad hoc networks,
2013 IEEE Wireless Communications and Networking Conference (WCNC). 07-APR-13, Shanghai, Shanghai, China. : ,

08/30/2013 48.00 Yang Qin, Yuanyuan Yang, Gwee Choon Lim, Xiang He. A flow admission control scheme for QoS in wireless ad hoc networks,
GLOBECOM 2012 - 2012 IEEE Global Communications Conference. 03-DEC-12, Anaheim, CA, USA. : ,

08/31/2011 13.00 Miao Zhao, Yuanyuan Yang. A framework for mobile data gathering with load balanced clustering and MIMO uploading,
IEEE INFOCOM 2011 - IEEE Conference on Computer Communications. 10-APR-11, Shanghai, China. : ,

08/31/2011 14.00 Dawei Gong, Yuanyuan Yang, Miao Zhao. A cost minimization algorithm for mobile data gathering in wireless sensor networks,
2010 IEEE 7th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 08-NOV-10, San Francisco, CA, USA. : ,

08/31/2011 9.00 Miao Zhao, Yuanyuan Yang. Bounded relay hop mobile data gathering in wireless sensor networks,
2009 IEEE 6th International Conference on Mobile Adhoc and Sensor Systems (MASS). 12-OCT-09, Macau, China. : ,

08/31/2011 10.00 Yuanyuan Yang, Miao Zhao. Packet scheduling with joint design of MIMO and network coding,
2009 IEEE 6th International Conference on Mobile Adhoc and Sensor Systems (MASS). 12-OCT-09, Macau, China. : ,

08/31/2011 11.00 Miao Zhao, Yuanyuan Yang. An Optimization Based Distributed Algorithm for Mobile Data Gathering in Wireless Sensor Networks,
IEEE INFOCOM 2010 - IEEE Conference on Computer Communications. 14-MAR-10, San Diego, CA, USA. : ,

08/31/2011 12.00 Yuanyuan Yang, Sangjin Hong, Xi Deng. A Flexible Platform for Hardware-Aware Network Experiments and a Case Study on Wireless Network Coding,
IEEE INFOCOM 2010 - IEEE Conference on Computer Communications. 14-MAR-10, San Diego, CA, USA. : ,

08/31/2011 15.00 Xi Deng, Yuanyuan Yang. On-line adaptive compression in delay sensitive wireless sensor networks,
2010 IEEE 7th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 08-NOV-10, San Francisco, CA, USA. : ,

08/31/2011 16.00 Dawei Gong, Miao Zhao, Yuanyuan Yang. A multi-channel cooperative MIMO MAC protocol for wireless sensor networks,
2010 IEEE 7th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 08-NOV-10, San Francisco, CA, USA. : ,

08/31/2011 17.00 Zhexi Pan, Yuanyuan Yang, Dawei Gong. Distributed Clustering Algorithms for Lossy Wireless Sensor Networks,
2010 9th IEEE International Symposium on Network Computing and Applications (NCA). 15-JUL-10, Cambridge, MA, USA. : ,

08/31/2011 18.00 Miao Zhao, Yuanyuan Yang. Data Gathering in Wireless Sensor Networks with Multiple Mobile Collectors and SDMA Technique Sensor Networks,
Networking Conference (WCNC). 18-APR-10, Sydney, Australia. : ,

08/31/2011 19.00 Miao Zhao, Yuanyuan Yang, Dawei Gong. Joint Channel Assignment and Space-Division Multiple Access Scheduling in Wireless Mesh Networks,
Networking Conference (WCNC). 18-APR-10, Sydney, Australia. : ,

11/06/2014 60.00 Dawei Gong, Yuanyuan Yang, Hewu Li. An Efficient Cooperative Retransmission MAC Protocol for IEEE 802.11n Wireless LANs,
2013 IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 14-OCT-13, Hangzhou, China. : ,

11/06/2014 61.00 Yuanyuan Yang, Songtao Guo, Xiaojian Wang. Topology Control for Maximizing Network Lifetime in Wireless Sensor Networks with Mobile Sink,
2013 IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 14-OCT-13, Hangzhou, China. : ,

11/06/2014 59.00 Ji Li, Cong Wang, Fan Ye, Yuanyuan Yang. NETWRAP: An NDN Based Real Time Wireless Recharging Framework for Wireless Sensor Networks,
2013 IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 14-OCT-13, Hangzhou, China. : ,

11/06/2014 57.00 Cong Wang, Yuanyuan Yang, Ji Li. Mobility Assisted Data Gathering in heterogeneous energy replenishable wireless sensor networks,
2014 23rd International Conference on Computer Communication and Networks (ICCCN). 04-AUG-14, China. : ,

11/06/2014 58.00 Dawei Gong, Yuanyuan Yang, Hewu Li. Link-Layer Multicast in Smart Antenna Based 802.11n Wireless LANs,
2013 IEEE 10th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS). 14-OCT-13, Hangzhou, China. : ,

TOTAL: **34**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received   Paper

   TOTAL:

Number of Manuscripts:

Books

Received   Book

   TOTAL:

Received   Book Chapter

   TOTAL:

Patents Submitted

Y. Yang and C. Wang, ``Apparatus and method for recharge-triggered wake-up for power management in wireless sensor networks,'' United States Patent Application Number US 13/921,622, filed June 19, 2013.
 Assignee: Stony Brook University.

Patents Awarded

Awards

1. Best Paper Award Runner up, J. Li, Y. Yang and C. Wang,
``Mobility assisted data gathering in heterogeneous energy replenishable wireless sensor networks,'' The 23rd International Conference on Computer Communications and Networks (ICCCN), Aug. 2014

2. Best Paper Award Runner up, D. Gong, Y. Yang and H. Li,
``Link-layer multicast in smart antenna based 802.11n wireless LANs,'' The 10th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2013), Application Track, Oct. 2013.

3. Best Paper Award Runner up, J. Li, C. Wang, F. Ye and Y. Yang,
``NETWRAP: An NDN based real time wireless recharging framework for wireless sensor networks,'' The 10th IEEE International Conference on Mobile Ad-hoc and Sensor Systems (IEEE MASS 2013), System Track, Oct. 2013.

4. Best Poster Award, C. Wang and Y. Yang, ``NETWRAP: An NDN Based Real Time Wireless Recharging Framework for Wireless Sensor Networks,'' The 11th International Conference and Expo on Emerging Technologies for a Smarter World (CEWIT '14)}, Melville New York, Oct. 2014.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Ming Ma	0.50	
Chi Ma	0.50	
Miao Zhao	0.50	
Dawei Gong	0.50	
Xi Deng	0.50	
Ji Li	0.50	
Cong Wang	0.50	
FTE Equivalent:	**3.50**	
Total Number:	**7**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Yuanyuan Yang	0.25	
FTE Equivalent:	**0.25**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields: 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields: 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Zhexi Pan
Total Number: 1

Names of personnel receiving PHDs

NAME
Chi Ma
Ming Ma
Miao Zhao
Xi Deng
Dawei Gong
Total Number: 5

Names of other research staff

NAME	PERCENT SUPPORTED
Songtao Guo	0.00
Hai Huang	0.00
FTE Equivalent:	**0.00**
Total Number:	**2**

Sub Contractors (DD882)

Inventions (DD882)

The objective of this research is to study energy efficient self-adaptive schemes for wireless sensor networks. During the five years of the project, we have made significant progress along several research directions. We have investigated several research issues in mobile data gathering in wireless sensor networks, which are essentially, adaptive, cross-layer solutions to reduce sensor energy consumption and shortening data gathering latency. We have also studied adaptive compression for delay-sensitive data gathering, as well as the utilization of the lossy nature of wireless links to increase energy efficiency of the network. We have proposed a three-layer framework for mobile data gathering to achieve better scalability. Moreover, to achieve optimal performance for mobile data gathering, we have formulated two optimization problems in a utility maximization framework and designed distributed algorithms to solve these problems. Finally, we have developed an advanced wireless testbed for validating the algorithms. The research have resulted in 26 peer-reviewed journal papers, 34 peer-reviewed conference papers and one US patent application. We provide some highlights of our results in the following:

We have proposed a mechanism named bounded relay hop mobile data collection (BRH-MDC) to explore the inherent tradeoff between the energy saving and data collection latency in mobile data gathering. In BRH-MDC, we incorporated multi-hop relay into mobile data gathering, while the relay hop count is constrained to a certain level to limit the energy consumption at sensors. Specifically, a subset of sensors will be selected as the anchor points that buffer the locally aggregated data and upload the data to the mobile data observer, referred to as SenCar, when it arrives. In the meanwhile, when sensors are affiliated with these anchor points, it is guaranteed that the local relaying of any packet is bounded within a given number of hops. We also provided two efficient algorithms to select the anchor points among the sensors. It is observed in our simulations that when the local relays are required to complete within two hops for all sensors, our proposed algorithms can result in at least 38% shorter tour length on average compared to the single hop data gathering scheme with shortened
moving tour.

We have considered the data gathering with a joint design of controlled mobility and space-division multiple access (SDMA) technique. By
employing SDMA, two distinct compatible sensors may upload data to a SenCar concurrently, which may reduce the data uploading time into half in the ideal situation. We focused on minimizing the time of a data gathering tour which consists of the data uploading time and the moving time of the SenCar. The SenCar has to visit some specific locations where more sensors are compatible, and the moving tour of the SenCar may be adversely prolonged. We formalized the optimization problem of finding the tradeoff between the shortest moving tour and the full utilization of SDMA into an integer linear program (ILP) and proposed three heuristic algorithms that provide practically good solutions to the problem. Simulation results show that our proposed algorithms can save at least 35% of data gathering time compared to
other non-SDMA single-hop data gathering schemes.

We have also extended such joint design to the case of employing multiple SenCars in which the sensing field is divided into several non-overlapping regions, each having a SenCar. We focused on minimizing the maximum time of a data gathering tour among different regions over the sensing field, which is referred to as mobile data gathering with multiple mobile collectors and SDMA (MDG-MS). It is also an ILP problem and a region-division and tour-planning (RDTP) algorithm was given. Our simulations showed that the RDTP algorithm with two available SenCars can achieve at least 56% time saving with respect to the non-SMDA+single SenCar scheme.

We have studied the problem on how to achieve the optimal performance of the anchor-based mobile data gathering, where the SenCar stays at each anchor point for a period of sojourn time and meanwhile the nearby sensors transmit data to the SenCar in a multi-hop manner. We formalized the problems as a network utility maximization problem under the constraints of guaranteed network lifetime and bounded data gathering latency. We jointly addressed the three issues that are critical to data gathering performance: data rate control, flow routing, and sojourn time allocation. We then decomposed the utility maximization problem into several subproblems and solved them in a
distributed manner, which facilitates a scalable implementation of the optimization algorithms. Our extensive numerical results demonstrated that the algorithms can achieve fast convergence with the variables well within 5% of their optimal values after only 100 iterations.

To achieve good scalability, long network lifetime and low data collection latency. We have proposed a three-layer framework for mobile data collection in wireless sensor networks, which includes the sensor layer, cluster head layer, and mobile collector (called SenCar) layer. The framework employs distributed load balanced clustering and MIMO uploading techniques, which is referred to as LBC-MU. At the sensor layer, a distributed load balanced clustering (LBC) algorithm is proposed for sensors to self-organize themselves into clusters. In contrast to existing clustering methods, our scheme generates multiple cluster heads in each cluster to balance the work load and facilitate MIMO data uploading. At the cluster head layer, the inter-cluster transmission range is carefully chosen to guarantee the connectivity among the clusters. Multiple cluster heads within a cluster cooperate with each other to perform energy-saving inter-cluster
communications. Through inter-cluster transmissions, cluster head information is forwarded to the SenCar for its moving trajectory
planning. At the mobile collector layer, the SenCar is equipped with two antennas, which enables multiple cluster heads to simultaneously
upload data to the SenCar. The trajectory planning for the SenCar is optimized to fully utilize MIMO uploading capability by

properly
selecting polling points in each cluster. By visiting each selected polling point, the SenCar can efficiently gather data from cluster heads
and transport the data to the static data sink. Extensive simulations have been conducted to evaluate the effectiveness of the proposed LBCMU scheme. The results show that when each cluster has at most two cluster heads, LBC-MU can reduce the maximum number of transmissions a sensor performs by 90% and the average number of transmissions by 88% compared with the enhanced relay routing scheme. It also results in 25% shorter average data latency compared with the mobile collection scheme with single head clustering.

Recent experimental studies have revealed that a large percentage of wireless links are lossy and unreliable for data delivery in wireless
sensor networks (WSNs). Such findings raise new challenges for the design of algorithms in WSNs in terms of data reliability and energy efficiency. We have considered this problem and developed distributed clustering algorithms for WSNs by taking into account of the lossy nature of wireless links. We formulated the one-hop clustering problem that maintains reliability as well as saves energy into an integer program and prove its NP-hardness. We then proposed a metric based distributed clustering algorithm to solve the problem. We adopted a metric called selection weight for each sensor node that can indicate both link qualities around the node and its capability of being a cluster head. We further extended the algorithm to multi-hop clustering to achieve better scalability. Extensive simulations have been conducted under a realistic link model and the results demonstrate that the proposed clustering algorithm can reduce the total energy consumption in
the network and prolong network lifetime significantly compared to typical distributed clustering algorithms that do not consider lossy links.

We have considered applying compression, a popular technique to reduce data size by exploiting data redundancy, to delay sensitive data gathering in wireless sensor networks (WSNs). The limited computing resources at sensor nodes make the processing time of compression a nontrivial factor in the total delay a packet experiences and must be carefully examined when adopting compression. We have studied the effect of compression on data gathering in WSNs under a practical compression algorithm. We observed that that compression does not always reduce the packet delay in a WSN as commonly perceived, whereas its effect is jointly determined by the network configuration and hardware configuration. Based on this observation, we designed an adaptive algorithm to make on-line decisions such that compression is only performed when it can benefit the overall performance. We implemented the algorithm in a completely distributed manner that utilizes only local information of individual sensor nodes. Our extensive experimental results show that the algorithm demonstrates good adaptiveness to network dynamics and maximizes compression benefit.

Recent studies show that multi-channel MAC protocols can improve network capacity and boost energy efficiency, and cooperative multiple-input multiple-output (MIMO) technique can significantly enhance the energy efficiency. We have investigated a joint design of these two techniques by proposing a MAC protocol for wireless sensor networks that takes advantage of both multiple channels and cooperative MIMO. Specifically, sensor nodes in a WSN are organized into clusters and each cluster head selects some cooperative nodes to help forward traffic to or receive from other clusters by utilizing cooperative MIMO technique. For intra-cluster communications,
different channels are assigned to adjacent clusters to reduce collisions, while for inter-cluster communications, cooperative MIMO links are scheduled to improve energy efficiency and concurrent transmissions are enabled by assigning different channels to them. We have carried out extensive simulations and the results demonstrate that the proposed protocol can significantly increase throughput and improve energy efficiency compared to other schemes.

We have also developed an advanced wireless testbed for validating our data gathering mechanism and the algorithms designed. The testbed consists of two types of self-designed devices: wireless node and SenCar. The node works in 2.4GHz industrial, scientific and medical (ISM) and transfers data at 10 Kbps/250 Kbps/1 Mbps. It has enhanced computing capability provided by a 16-bit microprocessor and a Flash-FPGA based coprocessor with low power consumption. It also has extended memory (1 MB SRAM) for data buffering. ANSI C and standard digital logic design methods are used for implementation to verify our data gathering mechanism and the algorithms. The SenCar works as an autonomous mobile data collector that travels along the planned path through the area where the sensor network has been deployed to collect sensing data. With the equipped MIMO receiver, SenCar can communicate with two sensor nodes simultaneously thus data collection is more efficient. It also has a high performance central processing module (Freescale MPC8548E) and a high speed baseband processor (Xilinx XC6VSX475T) for fully-customizable computation, such as baseband digital signal processing for MIMO wireless communications, vehicle allocation (with GPS or ultrasonic), mobility control and high layer algorithms/protocols processing.

Significant Results:

We have investigated several research issues in mobile data gathering in wireless sensor networks, which are essentially adaptive, cross-layer solutions to reduce sensor energy consumption and shortening data gathering latency. The following are some highlights of our research results obtained in this project.

(1) We have designed algorithms for planning the moving path/circle of SenCar and balancing traffic load in the network. We show that by driving SenCar along a better path and balancing the traffic load from sensors to SenCar, the network lifetime can be prolonged significantly. Our moving planning algorithm can be used in both connected networks and disconnected networks. In addition, SenCar can avoid obstacles while moving.

(2) We have studied data gathering with a joint design of controlled mobility and space-division multiple access (SDMA) technique. By employing SDMA, two distinct compatible sensors may upload data to a SenCar concurrently, which may reduce the data uploading time into half in the ideal situation. We focused on minimizing the time of a data gathering tour which consists of the data uploading time of sensors and the moving time of the SenCar.

(3) We have also extended such a joint design to the case of employing multiple SenCars in which the sensing field is divided into several non-overlapping regions, each having a SenCar. We focused on minimizing the maximum time of a data gathering tour among different regions over the sensing field.

(4) We have proposed a mechanism named bounded relay hop mobile data collection (BRH-MDC) to explore the inherent tradeoff between the energy saving and data collection latency in mobile data gathering. In BRH-MDC, we incorporated multi-hop relay into mobile data gathering, while the relay hop count is constrained to a certain level to limit the energy consumption at sensors.

(5) We have studied the problem on how to achieve the optimal performance of the anchor-based mobile data gathering. We formalized the problems as a network utility maximization problem under the constraints of guaranteed network lifetime and bounded data gathering latency. We jointly addressed the three issues that are critical to data gathering performance: data rate control, flow routing, and sojourn time allocation. We then decomposed the utility maximization problem into several subproblems and solved them in a distributed manner, which facilitates a scalable implementation of the optimization algorithms.

(6) We have proposed a three-layer framework for mobile data collection in wireless sensor networks, which includes the sensor layer, cluster head layer, and mobile collector layer. The framework employs distributed load balanced clustering and MIMO uploading techniques to achieve good scalability, long network lifetime and low data collection latency.

(7) We have developed distributed clustering algorithms for wireless sensor networks by taking into account of the lossy nature of wireless links. We formulated the clustering problem that maintains reliability as well as saves energy into an integer program and proposed a metric based distributed clustering algorithm to solve the problem.

(8) We have considered applying compression to reduce data size by exploiting data redundancy, to delay sensitive data gathering in wireless sensor networks (WSNs). We have observed that that compression does not always reduce the packet delay in a WSN as commonly perceived, whereas its effect is jointly determined by the network configuration and hardware configuration. Based on this observation, we designed an adaptive algorithm to make on-line decisions such that compression is only performed when it can benefit the overall performance.

(9) We have proposed a MAC protocol for wireless sensor networks that takes advantage of both multiple channels and cooperative multiple-input multiple-output (MIMO) technique to improve network capacity and boost energy efficiency.

(10) We have also developed an advanced wireless testbed for validating our data gathering mechanism and the algorithms designed. The testbed consists of two types of self-designed devices: wireless node and SenCar. The node works in 2.4GHz industrial, scientific and medical (ISM) and transfers data at 10 Kbps/250 Kbps/1 Mbps. It has enhanced computing capability provided by a 16-bit microprocessor and a Flash-FPGA based coprocessor with low power consumption. It also has extended memory (1 MB SRAM) for data buffering. ANSI C and standard digital logic design methods are used for implementation to verify our data gathering mechanism and the algorithms. The SenCar works as an autonomous mobile data collector that travels along the planned path through the area where the sensor network has been deployed to collect sensing data. With the equipped MIMO receiver, SenCar can communicate with two sensor nodes simultaneously thus data collection is more efficient. It also has a high performance central processing module (Freescale MPC8548E) and a high speed baseband processor (Xilinx XC6VSX475T) for fully-customizable computation, such as baseband digital signal processing for MIMO wireless communications, vehicle allocation (with GPS or ultrasonic), mobility control and high layer algorithms/protocols processing.

This advanced testbed can also be used for other wireless networking projects.

Key outcomes and achievements:

This project systematically studies mobile data gathering in wireless sensor networks and provides practically good solutions to reduce energy consumption and improve the performance of data gathering in wireless sensor networks. By efficiently solving the main problems wireless sensor networks are currently facing, i.e., improving network performance with extended network lifetime, this project will greatly impel the application of wireless sensor networks in industry and national security.

We have introduced the design methodology of "smart-server dull-client" into wireless sensor networks (WSNs). Conventional WSNs are built with wireless sensor nodes that have been designed "as simple as possible" due to the constraint of hardware cost and are incapable of complex signal processing. In our project, sensor nodes are kept simple, and signal processing for space-division multiple-access is performed on mobile data collectors. The budget constraint on hardware of the networks can still be satisfied since only a few mobile data collectors are needed for large scale networks, while we can take advantage of high performance wireless communication techniques in WSNs. With this design methodology, it is possible to further improve network performance by incorporating advanced signal/algorithm processing techniques with low hardware cost of the networks.

We have developed an integrated data gathering mechanism for single-hop and multi-hop data gathering by utilizing analytical, simulation and testbed techniques. We have identified and addressed several research issues, focusing on path planning for mobile collectors, reducing sensor energy consumption, balancing traffic load and shortening data gathering latency in a cross-layer manner.

The broader impact of the project includes integrating graduate students into the project and disseminating important findings to the research community by way of conferences, journals and web site access. We have been improving the quality and productivity of graduate students through supervising students to perform research and to publish quality results in wireless networking area. So far, five Ph.D. students involved in the project have graduated, including a female student. They have take positions in major IT companies, such as Google, HP and Huawei.

The broader impact of the project is also evidenced by developing an advanced wireless sensor testbed. The testbed is a critical component in this project and is used for testing the feasibility and performance of the algorithms and protocols designed. It also will be an important facility for our related projects in future.

Technology Transfer